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Measuring Sub-Second Wind Velocity Changes for Agricultural Drift One Meter Above the Ground

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Abstract

Agricultural spray drift is affected by many factors including current weather conditions, topography of the surrounding area, fluid properties at the nozzle, and the height at which the spray is released. During the late spring/summer spray seasons of 2014 and 2015, wind direction, speed, and solar radiation (2014 only) were measured at 10 Hz, one meter above the ground to investigate conditions that are typically encountered by a droplet when released from a nozzle on an agricultural sprayer. Measurements of wind velocity as the wind passed from an upwind sensor to a downwind sensor were used to evaluate what conditions wind may be most likely to have a significant direction or speed change which affects droplet trajectory. For two individual datasets in which the average wind speed was 3.6 m/s (8.0 mi/h) and 1.5 m/s (3.4 mi/h), there exists little linear correlation of wind speed or wind direction between an upwind and downwind anemometer separated by 30.5 meters (100 ft). The highest observed correlation, resulting from a 12 second lag between the upwind and downwind datasets, was 0.29 when the average wind speed was 3.6 m/s (8.0 mi/h). Correlations greater than 0.1 were only found for wind speeds exceeding 3 m/s. Using this lag time, it was observed that the wind direction 30 seconds into the future had a 30% chance to be different by more than 20 degrees from current conditions. A wind speed difference of more than 1 m/s (2.2 mi/h) from current conditions (mean wind speed was 3.6 m/s (8.0 mi/h)) was observed about 50% of the time. Analyzing 36 days of the 2014 and 2015 spray season wind velocity data showed that the most variability in wind direction occurred with wind speeds below 2 m/s (4.5 mi/h). Greater wind direction variability occurred in the mid-afternoon with higher solar radiation.

Keywords

Sprayers, Spray Drift, Wind Effects, Turbulence, Spray Droplets

Disciplines

Agriculture | Bioresource and Agricultural Engineering

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MEASURING SUB-SECOND WIND VELOCITY CHANGES FOR AGRICULTURAL DRIFT ONE METER ABOVE THE GROUND

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ABSTRACT.

Agricultural spray drift is affected by many factors including current weather conditions, topography of the surrounding area, fluid properties at the nozzle, and the height at which the spray is released. During the late spring/summer spray seasons of 2014 and 2015, wind direction, speed, and solar radiation (2014 only) were measured at 10 Hz, one meter above the ground to investigate conditions that are typically encountered by a droplet when released from a nozzle on an agricultural sprayer. Measurements of wind velocity as the wind passed from an upwind sensor to a downwind sensor were used to evaluate what conditions wind may be most likely to have a significant direction or speed change which affects droplet trajectory. For two individual datasets in which the average wind speed was 3.6 m/s (8.0 mi/h) and 1.5 m/s (3.4 mi/h), there exists little linear correlation of wind speed or wind direction between an upwind and downwind anemometer separated by 30.5 meters (100 ft). The highest observed correlation, resulting from a 12 second lag between the upwind and downwind datasets, was 0.29 when the average wind speed was 3.6 m/s (8.0 mi/h). Correlations greater than 0.1 were only found for wind speeds exceeding 3 m/s. Using this lag time, it was observed that the wind direction 30 seconds into the future had a 30% chance to be different by more than 20 degrees from current conditions. A wind speed difference of more than 1 m/s (2.2 mi/h) from current conditions (mean wind speed was 3.6 m/s (8.0 mi/h)) was observed about 50% of the time. Analyzing 36 days of the 2014 and 2015 spray season wind velocity data showed that the most variability in wind direction occurred with wind speeds below 2 m/s (4.5 mi/h). Greater wind direction variability occurred in the mid-afternoon with higher solar radiation.

Keywords.

Sprayers, Spray Drift, Wind Effects, Turbulence, Spray Droplets

INTRODUCTION

Agricultural sprayers are used to distribute agricultural chemicals onto fields that protect and improve crop plant health; however, off-site drift of these chemicals can be detrimental to adjacent crops and other nearby plant and animal life. The EPA defines spray drift as "the physical movement of a pesticide through air at the time of application or soon thereafter, to any site other than that intended for application" (EPA, 2014). Boom height, air temperature, relative humidity, droplet size, droplet release pressure, air pressure, and wind conditions are just some of the factors that control spray drift with droplet size being the biggest contributing factor (Spray Drift Task Force, 1997). Spray technology includes capabilities to mitigate spray drift by affecting droplet size for wind conditions (Nordby & Skuterud, 1974; Smith, Harris, & Goering, 1982), and although the sprayer can control only some of these factors (e.g. boom height and spray quality (droplet size)), others such as ambient air conditions are beyond control. Instrumentation placed on a sprayer may be used to control droplet size based on weather conditions at the moment of spray release, giving extra control over spray drift, but this strategy can be obstructed by unforeseen changes in wind direction or speed within sub-minute time periods after the droplet has left the nozzle (Kruckeberg, 2011).

To better understand how wind may affect downwind spray drift, scientists have developed a number of different simulation models in the past thirty-five years. Popular methods include Lagrangian, Gaussian, Random Walk, Regression, and CFD models (Holterman, et al., 1997; Baetens, et al., 2007; Teske, et al., 2002; Tsai, et al., 2005; Frederic, et al., 2009; Smith, et al., 1982). By using such models, applicators gain knowledge of when drift potential is high and can adjust buffer zones to minimize the risk for spray drift (Craig, 2004; Brown, et al., 2004). The models include wind turbulence interactions by either using real data collected at a single physical location that is used for the entire range of the simulation (Tsai, et al., 2005; Frederic, et al., 2009), or by using the averaged wind velocity and updating the velocity at every time step with an assumed random fluctuation to simulate the turbulent nature of wind (Holterman, et al., 1997). Much attention is given to the development and progression of the droplets, but less attention is devoted to the random nature of transient wind velocity changes surrounding the droplet, such as the distribution of wind speed and direction with which the droplet interacts.

Previous research has attempted to incorporate the random nature of wind speed and wind direction, but little work has been done on measuring the wind conditions near ground boom release height that a droplet experiences during the short, sub-minute time periods from release at the nozzle to deposition. Data recorded for short-term wind velocity changes near the ground's surface are needed to better understand their effects on spray droplet trajectories. Assessing the likelihood of significant change in wind speed or direction near the ground during droplet trajectories would assist the potential for the use of on-board sprayer droplet control systems responding to wind conditions at the moment of spray release.

The central hypothesis of this research is that knowledge of the wind speed and direction at a point in time and space (e.g. using a meteorological station on-board the sprayer) should contribute to knowledge of wind speed and direction at another location nearby in time and space (i.e., along spray droplet trajectories after release from the nozzle). The ability to impact drift by on-board droplet-size adjustment depends on how much ambient wind velocity changes during the next approximately 5 to 40 seconds that smaller droplets remain entrained in the air. This work seeks to establish these relationships from measured data and ascertain the strength of these relationships.

Objectives

The objectives of this research were to

- Measure and characterize changes in transient wind velocity (direction and speed) at a typical ground sprayer boom height near the field surface, in both time and space, during the typical time periods that spray droplets are in the air from the time of release until deposition, and
- Evaluate under what conditions wind may most likely have a significant velocity change or be more turbulent.

METHODS AND MATERIALS

EXPERIMENTAL DESIGN AND APPARATUS

Field measurements of wind speed and direction were collected during the late spring/summer spraying season of 2014 and throughout the 2015 season using instrumentation set into a field of growing oats. The fields were located at the Iowa State University Research Farm's Bruner Farm fields F1 and F3 (respectively for 2014 and 2015) near Ames, Iowa (Figure 1). The field dimensions were 268 m long (north to south) by 105 m wide (east to west) (880 by 348 ft) for field F1 and 107 m long by 201 m wide (350 by 660 ft) for field F3.

Wind speed and solar radiation measurements were acquired at 10 samples per second using ultrasonic anemometers (model: WindMaster 3d, Gill Instruments, Lymington, Hampshire, UK) and a pyranometer (model: SP-212, Apogee Instruments, Logan, UT). The anemometers measured the wind speed in the north-south, east-west, and vertical directions (Figure 2) by sending and receiving ultrasonic sound waves from known locations separated by known distances. By using the time it takes a wave to travel that known distance, wind speed and direction can be calculated. Open source microcontrollers equipped with a GPS module (model Uno, Arduino; Ultimate GPS Shield, Adafruit, New York, USA) were used to log data to microSD data cards. Using the GPS's PPS (Pulse per Second) output, time correction was done to ensure time synchronization of the wind velocity measurements among the microcontrollers. To reduce influences on wind speed, the microcontrollers and power supplies were located separately from the anemometers at a distance of approximately 2-3 meters away. Sensors were placed in a cross pattern with 15.2 m (50 ft) spacing from a center point (Figure 3). Unfortunately, one of the five sensors had electronic problems and was not available for use during 2014 which resulted in four sensors placed 30.3 m apart in the cardinal directions, thus sensor five was only used in the center position in the 2015 season. Anemometers were placed one meter above the ground's surface to collect wind measurements to better simulate typical boom heights. Once oats reached maturity. The pyranometer was placed on the west most sensor's (Sensor 1) charging station near the anemometer.

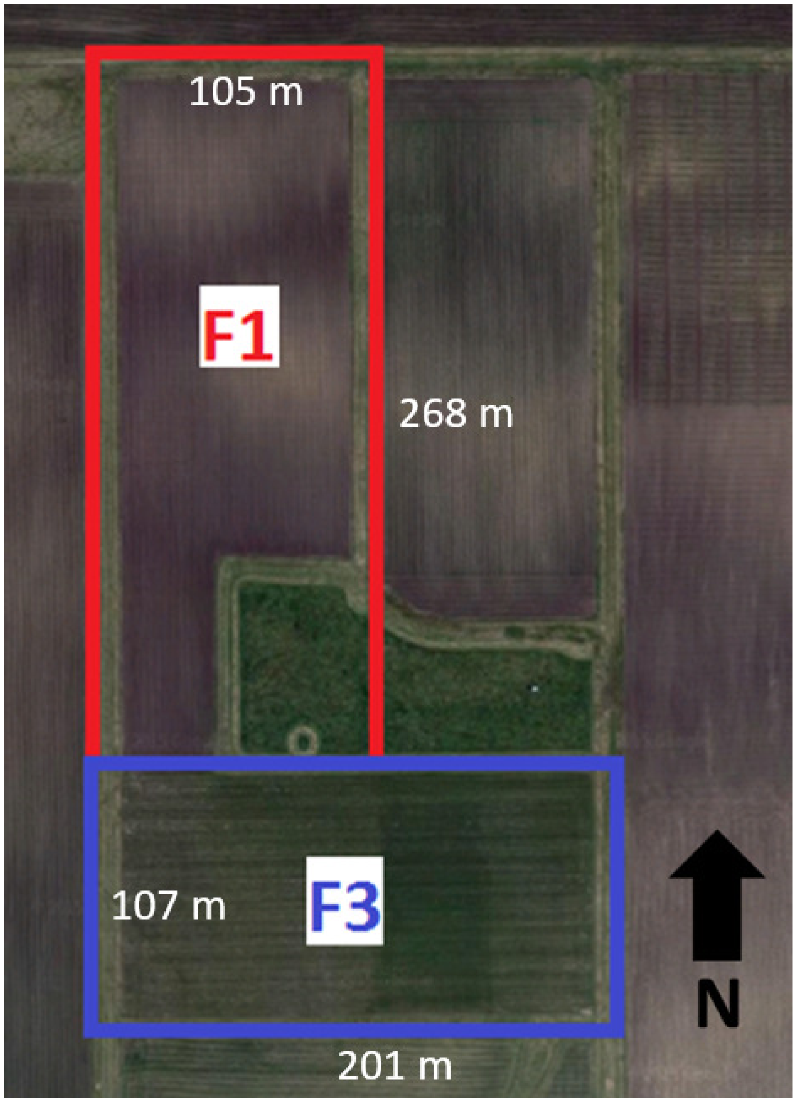


Figure 1: Wind measurements were acquired at Bruner Farm field F1 in 2014 and in field F3 in 2015 with the sensors located at 42° 00' 53.8" N and 93° 43' 52.4" W, and 42° 00' 45.6" N and 93° 43' 51.0" W, respectively (Google, 2015).

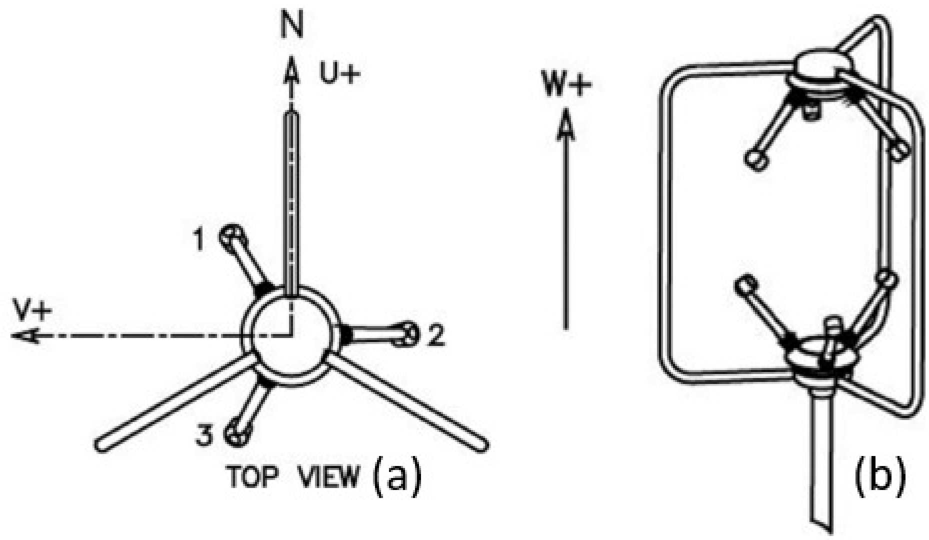


Figure 2: The ultrasonic Anemometer was oriented to measure wind velocity in the north-south (U), west-east (V) (a), and vertical (W) (b) directions by timing how long an ultrasonic sound wave takes to travel between two opposite-facing sensors. Three transmitter-receiver pairs are mounted at the bottom and top of the sensor structure, located at 1, 2, and 3 (Gill Instruments, 2014).

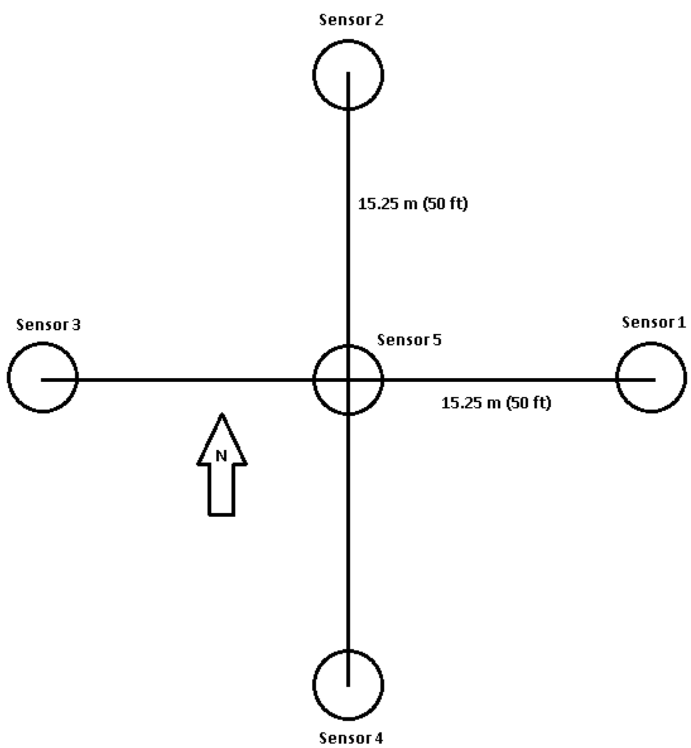


Figure 3: Anemometer sensors were positioned in a cross-pattern in test field. Sensors were spaced 15.25 m from the cross center in the cardinal directions. Sensor 5 at the center was only present for the 2015 data collection due to a sensor malfunction.

DATA ANALYSIS

Preprocessing: Wind speed was determined by calculating the magnitude of the velocity vector associated with the north-south and east-west direction components. Wind direction was found based on the magnitude of the two measured wind speeds and taking the arctangent of their ratios. A wraparound method was used to produce a semi-continuous wind direction dataset. Wraparound refers to the convention of allowing the wind direction to go above 359 degrees and below 0 degrees, i.e. 12 degrees = 372 degrees. Due to the use of ratios to find the wind direction, low wind speeds can lead to numerical instabilities when calculating the wind direction. The wind direction was defined by referring to the destination of the wind, so wind blowing from south-to-north was described as at an angle of 0 degrees, while wind blowing from west-to-east was described as at an angle of 90 degrees. The wind direction angle increased in a clockwise (CW) orientation.

Because of small amounts of drift in the actual sampling time of wind velocity at each sensor location, an interpolation was used to estimate wind velocity at points between 10 Hz collection times. The need to interpolate samples in time is due to the data recorders not remaining synchronized perfectly with one another. MATLAB (Version 8.3 (R2014a), MathWorks, Natick, MA), offered many different schemes for interpolation and although the cubic spline offered the smoothest fit to the data, the assumption that wind speed and wind direction have continuous first and second derivatives cannot be confirmed. Ultimately, a piecewise linear polynomial was chosen because,. for linear interpolation, no assumption was needed on the derivatives of the data (Faires, 2011).

Datasets: To find if wind measurements recorded at an upwind sensor were correlated to measurements at a downwind sensor, two datasets were taken such that the direction of the wind was either north-south or west-east. Two datasets were used due to the limited recordings of data where the wind was parallel with the sensors in either north-south or east-west directions and was during a period of time in which a sprayer would be in the field. The first dataset from 2014 consists of a five-hour period (7:30 am to 12:30 pm CDT) in which the average wind speed was 3.6 m/s (8 mi/h) and was coming out of the south traveling north. The second dataset from 2015 is from a 1.5 hour long period (12:50 pm to 2:20 pm CDT) with a mean wind speed of 1.5 m/s (3.4 mi/h) and was also coming out of the south. The entire recorded dataset of both the 2014 and 2015 seasons, encompassing 36 days' worth of data, was then used to determine conditions more likely to be present during significant wind directional changes.

Correlation analysis of nearby sensors: Linear correlation was used as a starting point to discover relationships between the upwind and downwind sensors. For the purposes of this study, the Pearson correlation was used (Equation 1).

$$r_{xy} = \frac{\sum_{k=1}^{N}(x_k - \bar{x})(y_k - \bar{y})}{\sqrt{\sum_{k=1}^{N}(x_k - \bar{x})^2 \sum_{k=1}^{N}(y_k - \bar{y})^2}} \tag{1}$$

The 2014 and 2015 datasets were split into multiple one-minute time segments using the original 10 Hz measurements. Linear correlations were performed on each of these one-minute data segments. The linear correlations were then averaged together giving an averaged linear correlation for each of the 2014 and 2015 datasets to compare velocity and directional relationships between the upwind and downwind sensors. With these one-minute segments, the time it takes for the wind to travel from one sensor to the next can be included. During the 2014 dataset, there was a 3.6 m/s (8mi/h) average wind speed and a 1.5 m/s (3.4 mi/h) average wind speed for the 2015 dataset. This should lead to an observed lag time of 8.5 seconds for observations of the upwind sensor to travel the 30.5 meters to the downwind sensor for the 2014 dataset and a lag time of 20.33 seconds for the 2015 dataset. To confirm this, linear correlations were taken from the upwind sensor to the downwind sensor while shifting the downwind sensor's starting data to correspond with the amount of lag that was currently being tested (upwind sensor starts at time = 0 while downwind sensor starts at time = lag). Lag values of 0 to 30 seconds were investigated.

Wind change histograms: To visualize the relationships between both the wind speed and direction at two different sensor locations, two-dimensional histograms plots were developed. For each dataset, separate histograms were made by finding the frequency of wind speed and direction combinations at the two sensors. For the 2014 dataset, the wind speed range was set to 0 to 10 m/s and the wind direction range was set to 100 to 250 degrees. For the 2015 dataset, the wind speed range was set to 0 to 5 m/s and the wind direction range was set to 50 to 300 degrees. For both datasets, the ranges were divided into 0.1 m/s intervals and one-degree intervals for speed and direction, respectively. Then for each wind variable, an array data structure was used to record the frequency that a particular combination was found from the two sensors. This analysis went through each dataset and counted the number of times that combinations occurred.

Outside of range probability analysis: To anticipate an unexpected change in wind direction or wind speed after spray is released from the nozzle, it would be desirable to know the probability of the downwind sensor being within a given tolerance range of the upwind sensor. To investigate this probability, the 2014 and 2015 datasets were analyzed by comparing the difference in wind speed and direction between the upwind sensor and the downwind sensor(s) and counting how many data points were outside a specified tolerance range for wind speed and direction. For the 2014 dataset, sensor 2 was designated the upwind sensor and sensor 4 was designated the downwind sensor. The wind speed tolerance was chosen from the range of 0 to 4 m/s and the wind direction tolerance was chosen in the range of 0 to 45 degrees. A lag value was used that gave the maximum linear correlation to the downwind sensor. For the 2015 dataset, access to the center sensor (sensor 5) made it possible to do comparisons between the multiple configurations available of upwind to downwind sensors (sensor 2 to sensor 5, sensor 5 to sensor 4, and sensor 2 to sensor 4). The wind speed tolerance was chosen from the range of 0 to 1 m/s and the wind direction tolerance was chosen in the range of 0 to 45 degrees. A lag value of 0 seconds was used for the downwind sensors.

Parameters affecting wind changes analysis: Greater insight into the meteorological conditions present when transient wind velocity changes occur may be helpful in understanding the possible droplet trajectories after droplets have left the nozzle. To investigate these relationships, data collected over a range of 36 days (more than 100 million data points) in the late spring/summer spraying seasons of 2014 and 2015 were analyzed (the 5-hour 2014 and 1.5-hour 2015 datasets were subsets of this larger 36-day dataset). The goal of the analysis was to determine when it was more likely to encounter changes in wind direction of greater than three different tolerances, 30 seconds into the future. This analysis progressed through the data comparing wind direction measurements that were 30 seconds in time apart from each other. When the measurements were greater than a wind direction tolerance, the current wind direction, speed, solar radiation, and time of day were recorded. This analysis was repeated for three tolerances of 45, 25, and 5 degrees. The frequency of occurrence of these wind changes as the percentage of the entire dataset were calculated for nine bins spanning the range of each of the three environmental variables. The results were presented as histograms for each other three tolerance values.

RESULTS AND DISCUSION

CORRELATION ANALYSIS OF NEARBY SENSORS

Relationship at 0.1 sec intervals between sensors over five hour period (2014)

The average wind speed during the five-hour time period was observed to be 3.6 m/s (8 mi/h). Due to the large number of points, it was unclear graphically if there existed a correlation (Figure 4). Linear correlation of individual 10 Hz measurements between the sensors was 0.29 and 0.27 for wind direction and wind speed respectively utilizing equation 1. It can be seen from the figure that the sensors follow similar trends over the long term indicating that the sensors experience the same average phenomena. For example, the variability in speed at both sensors decreases from about 8:45 am until about 9:30 am. The wind direction, which is varying rapidly, also decreases during the same time period.

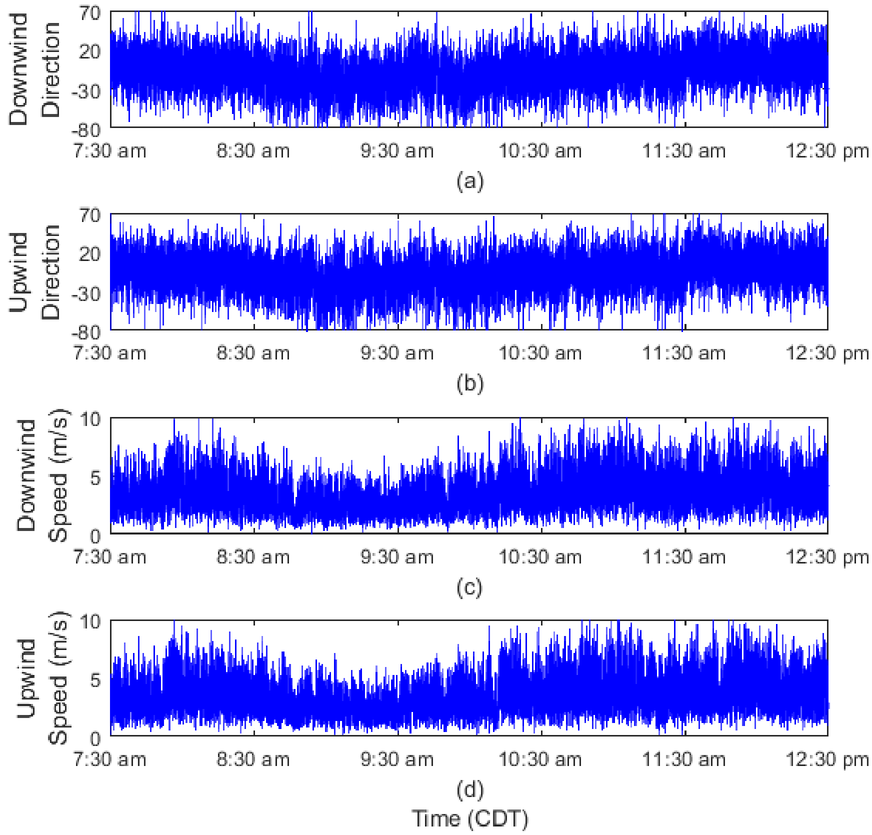


Figure 4: Five-hour (2014) period of upwind/downwind sensors for both wind speed and wind direction from 7:30 am to 12:30 pm CDT where (a) shows the north sensor's wind direction, (b) shows the south sensor's wind direction, (c) shows the north sensor's wind speed magnitude, and (d) shows the south sensor's wind speed magnitude.

Relationship at 0.1 sec intervals between sensors over 1.5-hour period (2015):

This analysis was also done for a data sample with average wind speed of 1.5 m/s (3.4 mi/h) from 12:50 to 2:20 p.m. (2015 dataset) during which wind generally came from the south and passed over the southern, central, and northern sensors (Figure 5). The correlation coefficients (eq 1) for wind direction and wind speed for all combinations of two of the three sensors were all below 0.03 (north to central gave 0.01 and -0.0003, central to south gave 0.03 and 0.008, and north to south gave 0.02 and -0.007 for correlations of wind direction and wind speed respectively).

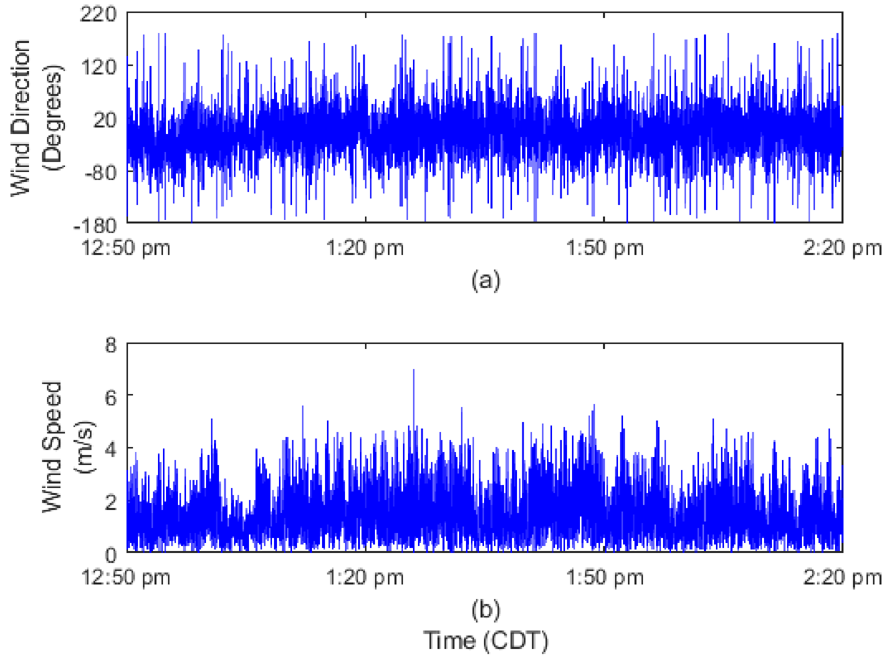


Figure 5: One and a half hour period of wind speed and wind direction at the center sensor of the 2015 dataset where (a) shows the center sensor's wind direction and (b) shows the center sensor's wind speed magnitude.

Maximum correlation using lag adjustment:

Looking at the linear correlations (eq 1) of the smaller one-minute data segments, with no lag consideration, very low linear correlation values were found for both the 2014 and 2015 datasets. However, as the lag term increase, so does the linear correlation for the 2014 dataset. The linear correlation increases until the lag value is 12 seconds (Figure 6). This is greater that the theoretical value of 8.5 seconds that was calculated earlier and could be caused by the turbulent interactions of the wind across the oat crop canopy.

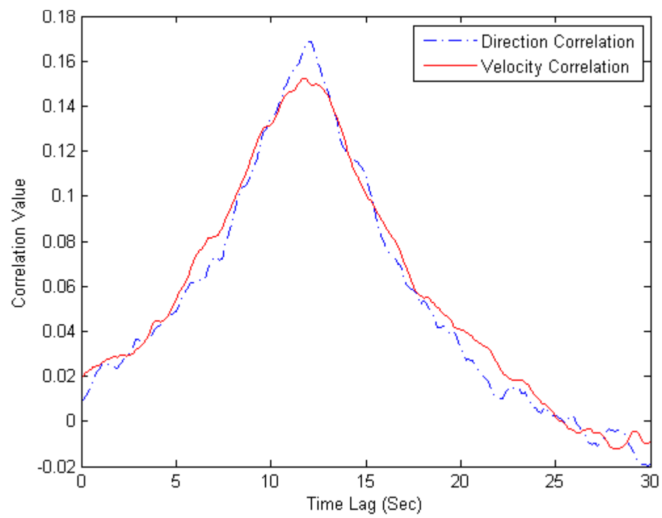


Figure 6: Correlation plot as a function of lag between the sensors for wind direction and wind speed of the 2014 dataset.

From investigating the five-hour segment of data, wind direction and wind speed cannot be considered to remain constant at a downwind location after leaving the upwind sensor. Taylor's Hypothesis of Frozen Turbulence states that turbulence can be considered "frozen" as eddies (turbulent motion of wind) travel pass a sensor(s) (Stull, 2009). The lack of correlation between upwind and downwind sensors, even after adjusting for lag in wind conditions shown in Figure 6, implies that turbulence is not frozen on these small length and time scales.

The 2015 dataset did not show any significant lag adjustment (Figure 7) as was seen in Figure 6 for the 2014 dataset. Mean wind speed of 2015 data was slower than 2014 data, and the inability to identify a lag period may have been related to the light and variable nature of slower wind speeds.

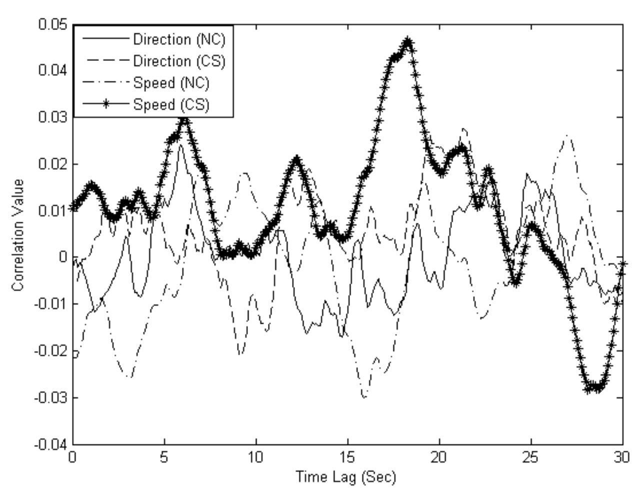


Figure 7: Correlation plot as a function of lag between the different sensors for wind speed and direction of the 2015 dataset.

WIND CHANGE HISTOGRAMS

The five-hour, 2014, dataset was viewed from a histogram standpoint to better view the structure of the data (Figure 8). The legend to the right of the graphs (bar graph) shows the values of the frequency of observations within each cell. The data grouped around the mean with a slight linear dependency structure shown as an elongation for wind direction and a tighter grouping for wind speed.

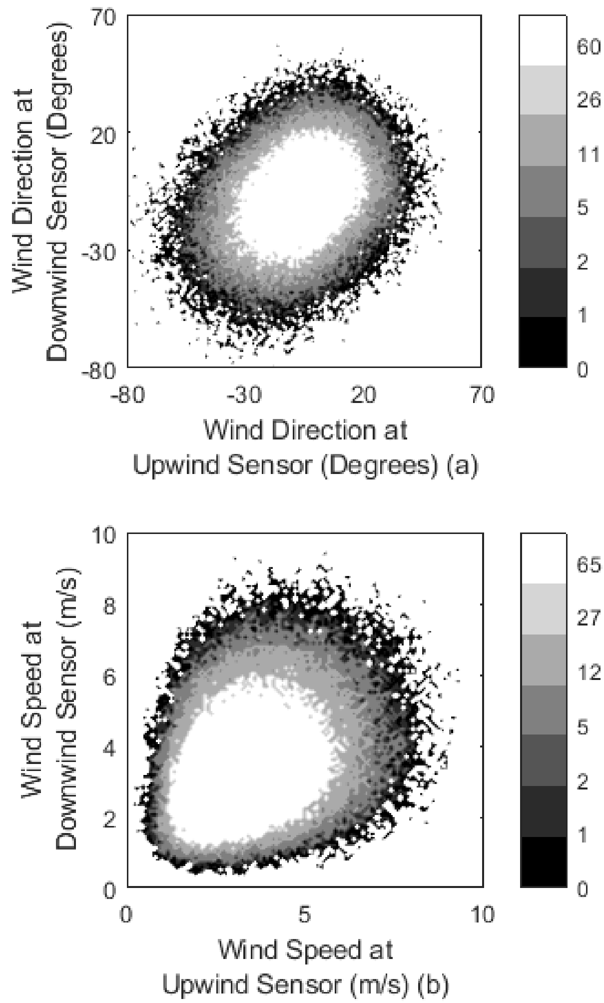


Figure 8: Histogram showing the frequency of observations comparing downwind direction (a) and downwind speed (b) as a function of upwind conditions of the five-hour, 2014, season. The range was divided into sectors (e.g., for wind direction, grid spacing of 1x1 degree were used) and the number of points were then counted for each sector.

The 1.5-hour, 2015 dataset is exemplified by a histogram for the central and northern sensors showing a grouping around the mean wind direction with no elongation and wind speed being much more spread out (Figure 9). Similar figures were attained at the other sensors. An absence of change in general wind direction and speed during the shorter time period in 2015 resulted in the area of highest frequency of values in the histograms being more circular (less elliptically elongated) than in

2014.

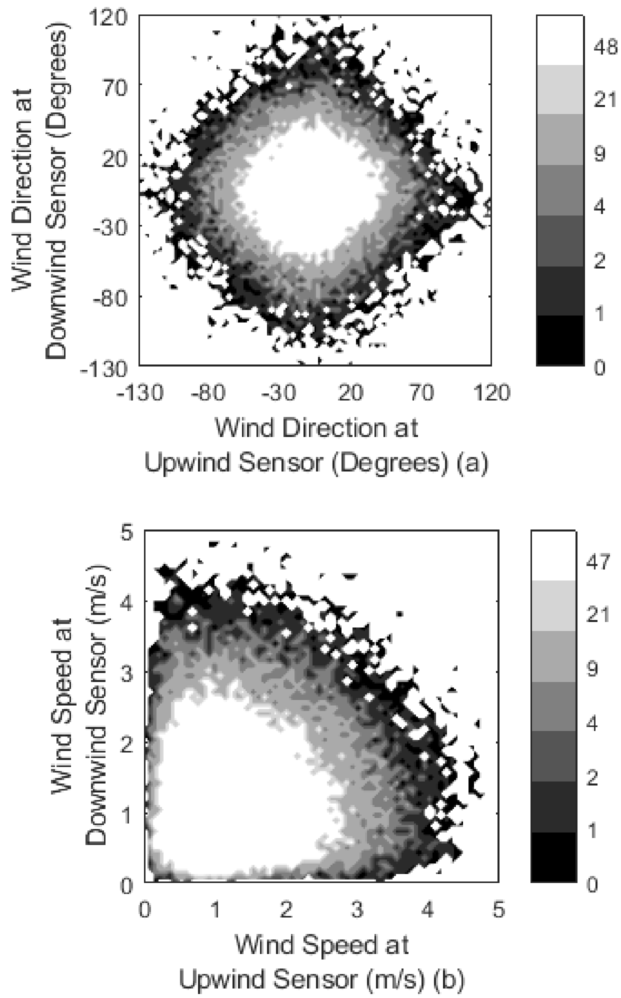


Figure 9: Histogram showing the frequency of observations comparing downwind direction (a) and downwind speed (b) as a function of upwind conditions of the 1.5-hour, 2015, season. The range was divided into sectors (e.g., for wind direction, grid spacing of 1x1 degree were used) and the number of points were then counted for each sector.

OUTSIDE OF RANGE PROBABABILITY ANALYSIS

For both wind direction and speed, the percentage of measurements outside of the tolerance decreased in a linear fashion with increases in the size of the tolerance, and then it curved toward an asymptotic curve that more slowly approaches zero (Figure 10). From Figure 10, it is seen that a wind direction tolerance of 25 degrees and a wind speed tolerance of 2 m/s is needed to have 20% of observations fall outside of tolerances.

For 2015, the relationship between the percentage of measurements outside of the tolerance and the size of the tolerance was similar to that observed for the 2014 data, but the decrease in percentage of measurements outside the tolerance decreased in a more linear fashion over the tolerance ranges (Figure 11). In addition, the comparisons between the different sensors followed similar curves and no effect of distance was observed. That is, the comparison between the north sensor (#2) and the south sensor (#4), 33.5 m apart, resulted in percentage outside tolerance values which were very similar to those comparisons with the center sensor (#5) which was 15.25 m from the other sensors.

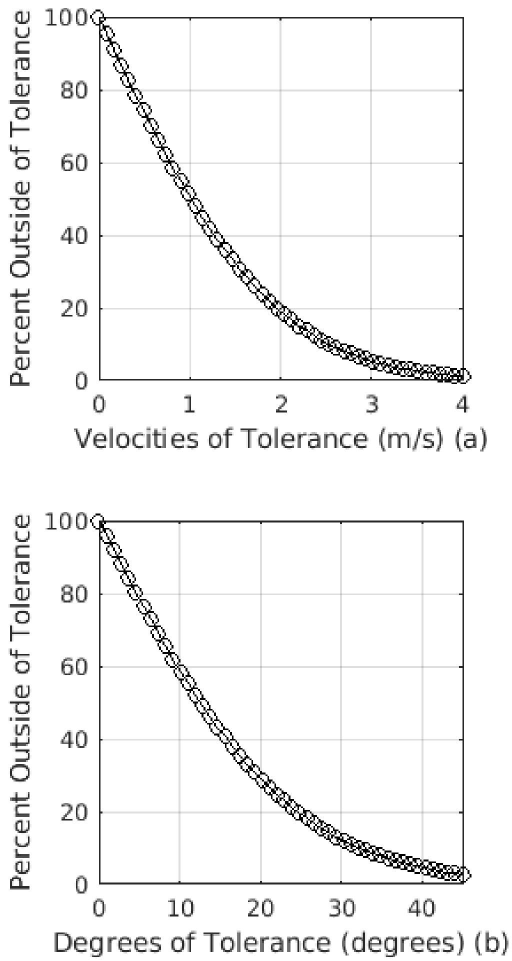
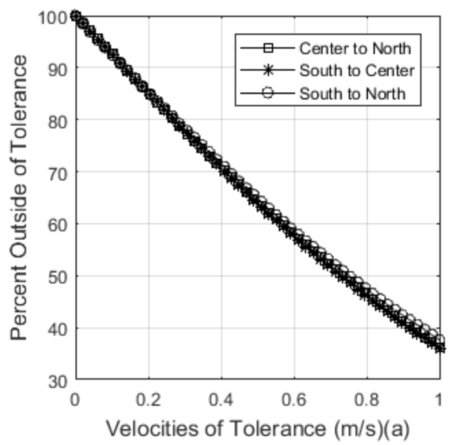


Figure 5: Probability that the downwind sensor will be outside a given tolerance to the upwind sensor for wind speed (a) and wind direction (b) of the 2014 dataset.



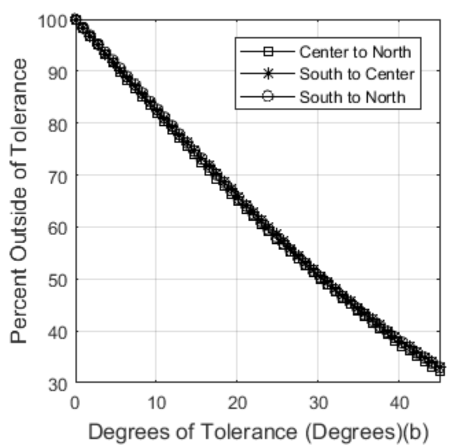


Figure 6: Probability that the downwind sensor is within a tolerance of an upwind sensor for wind speed (a) and wind direction (b) of the 2015 dataset.

PARAMETERS RELATED TO WIND CHANGES

Based on the analysis, there were differences in the frequency of wind changes larger than tolerances with changes in the values of the environmental variable. These effects were most clearly observed for the 45-degree tolerance. For this tolerance, wind change occurred most frequently for solar radiation values in the 875 W-m^{-2} range, for low wind speeds (<0.5 m/s), and around 15:00 hours in the day (Figure 12). The observations of more wind changes with greater solar radiation and in the afternoon are consistent with theory. As the sun heats the earth, increasing the surface energy, the weather becomes turbulent (Stull, 2009).

As the tolerance was tightened, to 25 degrees and 5 degrees, the distributions for time of day and solar radiation became more uniform (Figure 13 and 14). However, the tendency for wind directional shifts to occur more frequently at lower wind speeds remained relatively unchanged as the tolerance was reduced from 45 degrees to 25 degrees. This shows that most unstable events occur below 1 m/s (2.2 mi/h) winds, but this also may be an artifact from the calculation of wind direction caused by taking the ratio of small numbers. Application at low wind speeds is often recommended and may limit the distance of off-target drift even if the likelihood of unforeseen wind directional shift is greater.

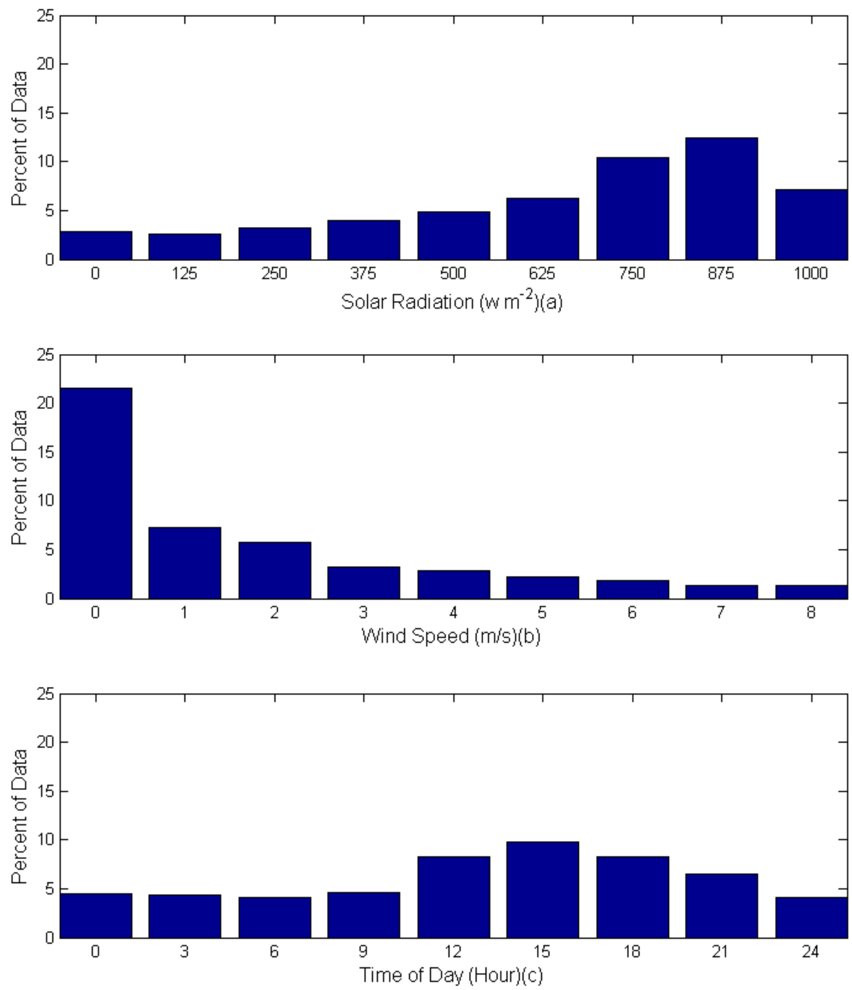


Figure 7: Percentage of all collected data within a certain range in which a wind change 30 seconds in the future was greater than 45 degrees with respect to solar radiation (a), wind speed (b), and time of day (c).

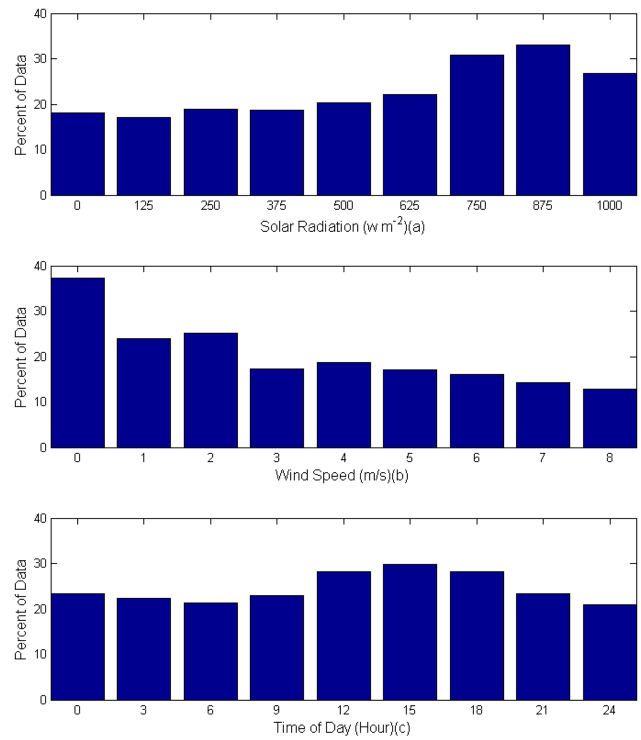


Figure 8: Percentage of all collected data within a certain range in which a wind change 30 seconds in the future was greater than 25 degrees with respect to solar radiation (a), wind speed (b), and time of day (c).

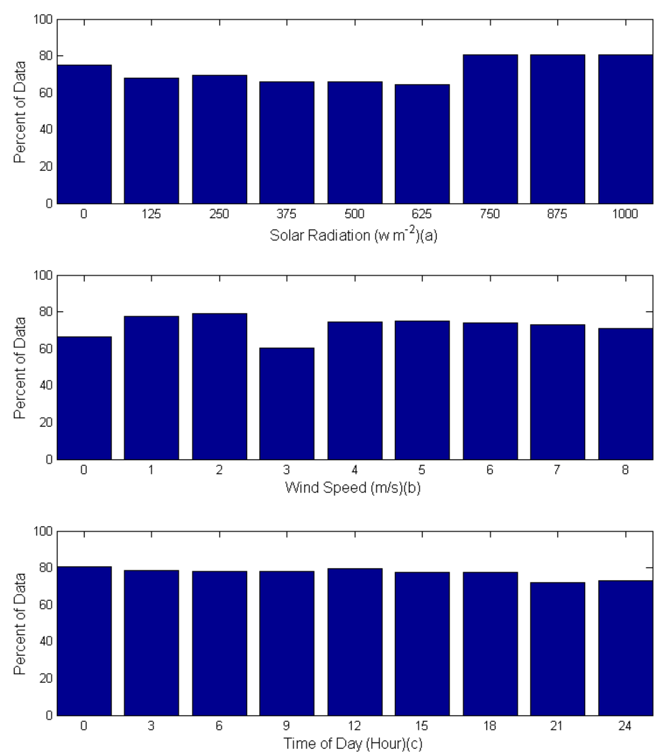


Figure 9: Percentage of all collected data within a certain range in which a wind change 30 seconds in the future was greater than

5 degrees with respect to solar radiation (a), wind speed (b), and Time of Day (c).

DISCUSSION

During a five-hour period (7:30 am to 12:30 pm) with an average wind speed of 3.6 m/s (8 mi/h) and a northernly wind direction, random fluctuation of wind direction and speed at upwind and downwind sensors, 30 m (100 ft) apart, had correlation coefficients of 0.29 and 0.27 respectively. Correlation was less during shorter one-minute periods in which a spray droplet may travel (0.01 and 0.02 respectively) but improved to coefficients of 0.17 for wind direction and 0.15 for wind speed if a lag time of 12 seconds was used between the two sensors. Using a lag time, downwind direction was greater than 20 degrees different than the upwind sensor 30% of the time while wind speed was greater than 1 m/s (about a quarter of the mean wind speed) different than the upwind speed about 50% of the time and quickly reduces to 20% at 2 m/s.

During a 1.5-hour period (12:50 pm to 2:20 pm) with an average wind speed of 1.5 m/s (3.3 mi/h) and a northernly direction, instantaneous measurements between the downwind and upwind sensors either 15 or 30 m (50 or 100 ft) apart were uncorrelated. However, downwind direction was greater than 20 degrees different than the upwind direction 65% of the time, while the downwind speed was greater than 0.25 m/s (about a quarter of the mean wind speed) different than the upwind speed 80% of the time.

Knowing that wind speed stays within 2 m/s 80% of the time and that wind direction stays within 20 degrees 70% of the time, can help applicators estimate the likelihood of wind changes in real-tine, decreasing the probability of spray drift for average wind speeds around 4 m/s. The results involving the 1.5 m/s average wind speed (2015) also gives information on the high variability of both the wind speed and wind direction. This variable nature of low wind conditions indicate that great care is needed at low wind speeds.

CONCLUSIONS

From this research, the following conclusions were drawn:

- While instantaneous or time-lagged correlations between distance-separated anemometers were very low, wind speed and wind direction measurements, separated up to 30 m, were within the ranges of 2.5 m/s and 30 degrees 90% of the time when wind speeds were measured at 3.6 m/s.
- Across a range of late spring/summer days in which suitable conditions for ground spraying were present, significant changes in wind direction within 30 seconds periods were more likely to occur during wind speeds in the range of 0-2 m/s (0-4.5 mi/h). Wind changes within 30 seconds occurred more frequently under conditions of higher solar

radiation and in the mid-afternoon.

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